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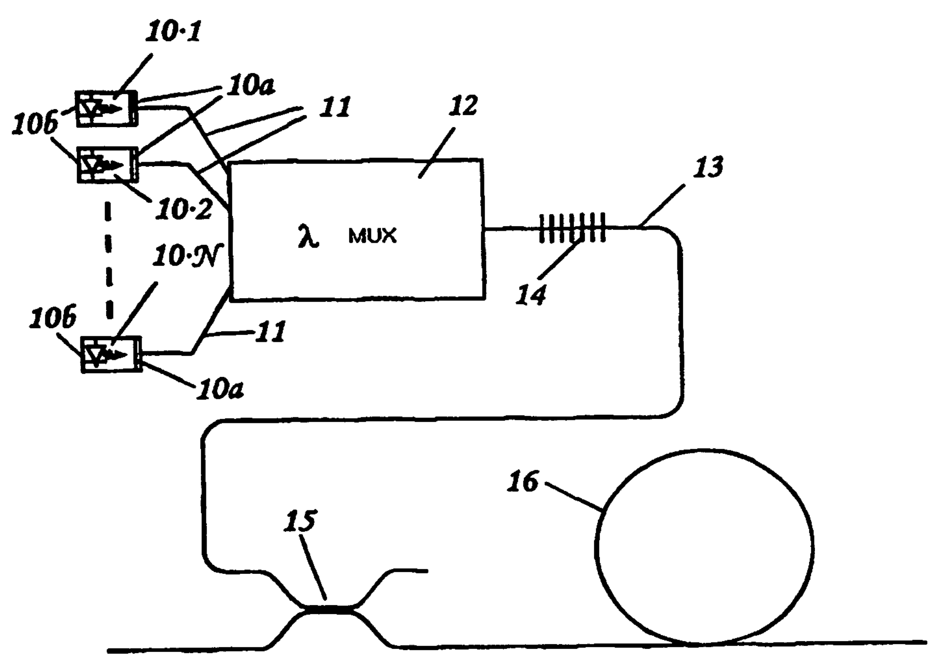

(57) Abstract

One facet (10b) of each of a set of N semiconductor laser chips (10) is provided with an antireflection coating (10a) through which the chip emission is coupled, via a wavelength multiplexer (12), with a partially reflecting Bragg reflector (14) providing an N-way wavelength multiplexed laser output for pumping an optical amplifier (16). The wavelength multiplexer may be constituted by a cascade arrangement of Mach-Zehnders (12, 40 and 41).

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LASER ASSEMBLY

Background to the Invention

This invention relates to laser assemblies with common outputs. A particular though not necessarily exclusive application for such devices is for optically pumping optical amplifiers.

In the field of optically pumped optical amplifiers the optical wavelength multiplexing of pump sources has been proposed as a way of increasing pump power in a single spatial mode. All the different pump wavelengths need to be confined within the appropriate absorption spectrum of the optical amplifier, and also involves the emission wavelength of the individual pumps being spectrally aligned with the spectral characteristics of the wavelength muliplexer. Typically this requires active wavelength control using feedback electro-optic control loops to achieve the requisite spectral precision. Such feedback is for instance employed in the wavelength multiplexed optical amplifier pump described in UK Patent Application GB 2 293 684.

Summary of the Invention

The present invention is directed to an alternative way of obtaining the requisite spectral precision that is advantageous in that it is all-optical rather than electro-optical.

According to the present invention there is a provided a laser assembly having a set of N reflectors optically coupled via a set of N optical amplifiers and an Nx1 wavelength multiplexer with a partially reflecting common reflector so as to define N laser cavities providing an N-way wavelength-multiplexed output from the common reflector.

Preferably the N optical amplifiers are semiconductor chips each provided with an antireflection coated facet at one end of the chip and a reflecting facet at the other. A feature of the invention is that multiple wavelength operation is possible without the imposition of the requirement that each of the N chips be different from each of the other N-1 chips. They may be all identical, and can be constructed in monolithic form.

It is also an object of the present invention to provide, for an optical transmission system, an optically pumped optical amplifiers in which increased pump power is provided by wavelength multiplexing into a single optical mode a plurality of closely wavelength spaced optical sources in a manner that avoids the need either for tight wavelength tolerancing of the individual sources, or for active electro-optical feedback wavelength control of these sources.

The invention also provides an optical amplifier optically pumped by a laser assembly having a set of N reflectors optically coupled via a set of N optical amplifiers and an Nx1 wavelength multiplexer with a partially reflecting common reflector so as to define N laser cavities providing an N-way wavelength-multiplexed output from the common reflector.

One preferred form of wavelength multiplexer for the laser assembly is a Mach-Zehnder, or tree of Mach-Zehnders. In the case of a tree configuration laser assembly the place of the Mach-Zehnders at the apex of the tree may be taken by a polarisation beam splitter in association with two wavelength-dependent birefringent elements such as Lyot depolarisers.

The invention further provides, in an optically pumped optical amplifier having a set of N optical pump amplifier sources provided with optical feedback to make the sources lase, a method of controlling the wavelength relationship between the emission wavelengths of the N lasing optical pump sources by providing the feedback in part by a partial reflector that is common to each lasing source via an Nx1

wavelength multiplexing element to provide a combined wavelength multiplexed optical pump output from the partial reflector.

Brief Description of the Drawings

There follows a description of laser assemblies embodying the invention in preferred forms. The description refers to the accompanying drawings in which:-

Figure 1 depicts a schematic diagram of a laser assembly constituting the pump of an optically pumped fibre amplifier,

Figure 2 schematically depicts an embodiment of the laser assembly of Figure 1 employing a single Mach Zehnder as its wavelength multiplexer,

Figure 3 depicts a preferred arrangement of wavelength dependencies for the laser assembly of Figure 2,

Figure 4 schematically depicts an embodiment of the laser assembly of Figure 1 employing a tree of three Mach-Zehnders as its wavelength multiplexer.

Figure 5 schematically depicts an embodiment of the laser assembly of Figure 1 employing a polarisation beam splitter associated with two wavelength-dependent birefringent elements as its wavelength multiplexer, and

Figure 6 schematically depicts an embodiment of the laser assembly of Figure 1 employing a tree of three polarisation beam splitters with four associated wavelength-dependent birefringent elements as its wavelength multiplexer.

Detailed Description of Preferred Embodiments

Referring to Figure 1, set of N semiconductor injection optical amplifier chips 10·1, 10·2 ... 10·N are each provided with an anti-reflection coating 10a at the end opposite a reflecting facet 10b. The individual amplifier

chips 10 are represented as fully discrete chips but may alternatively be constituted by different parts of a monolithic structure.

Each amplifier 10 is optically coupled via its anti-reflection coated facet 10a with an associated single mode optical fibre pigtail 11. The other ends of the fibre pigtails 11 are optically coupled with the N ports of an Nx1 wavelength multiplexer 12. A further length 13 of single mode optical fibre is connected to the remaining part of the multiplexer 12, and in the fibre is formed a partially reflecting Bragg reflective grating 14. The optimum reflectivity needs to be less than 100% to allow light to emerge from the optical cavity through this reflector, but the reflectivity should be high enough to dominate the feedback. The other end of the fibre 13 is connected to one input of a pump/signal wavelength-multiplexing coupler 15. Signal traffic is applied to the other input port, and the multiplexed output appears at one of its output ports, to which is connected a length 16 of optically amplifying fibre.

The Bragg reflective grating 14 co-operates, via the multiplexer 12, with the reflecting facets 10b of the semiconductor optical amplifiers 10 to form N laser cavities sharing a common optical cavity defining reflector, grating 14, in such a way as to provide a multiplexed output from the common reflector directed towards the wavelength-multiplexing coupler 15.

An example of a laser assembly composed of two lasers wavelength multiplexed by a Mach-Zehnder is depicted in Figure 2. The Mach-Zehnder 12 of the assembly of Figure 2 is constituted by a tandem arrangement of two single mode fused fibre 4-port 3dB couplers 20 and 21 coupled by two unequal lengths 22 and 23 of single mode fibre. The difference in their lengths is represented by the small loop 24.

Figure 3 depicts the way the spectral characteristics of the individual components of the laser assembly of Figure 2 are nested. Curve 30 depicts the gain spectrum of the semiconductor amplifier clips 10. This is the characteristic with the widest spectral width. Next smaller is the width of the absorption characteristic 31 of the optical amplifier fibre 16.

Slightly smaller still is the spectral reflection characteristic 32 of the Bragg reflector 14. This is a non-saturating characteristic (i.e. the peak reflective coefficient is less than 100%), but it should have a relatively flat-topped reflective band with relatively fast roll-off both at the short- and long- wavelength edges of the reflective band. The Bragg reflector spectral characteristic lies entirely within the range of the absorption characteristic of the amplifier fibre 16. The absorption characteristic of the amplifier must overlap, and preferably lies entirely within, the gain spectrum 30 of the semiconductor chips 10.

The difference in optical path length between the two limbs 22 and 23 of the Mach-Zehnder is chosen to provide a substantially raised cosine spectral characteristic 33 that includes at least one peak and at least one trough within the spectral range defined by the flat topped portion of the spectral reflective characteristic of the Bragg reflector 14. In fact the Mach-Zehnder will have two characteristics (one for the straight through path, and the other for the cross-over path) with the troughs of one registering with the crests of the other. For reasons of clarity the second characteristic has been omitted from Figure 3. Finally there will be a substantially raised cosine spectral characteristic 34 for each of the composite laser cavities that are respectively defined between the Bragg reflector 14 and the reflecting facet 10b of each of the semiconductor amplifier chips 10. To ensure that each of the N optical cavities is capable of lasing, the optical path length from each reflecting facet 10b to the Bragg reflector 14 needs to be long enough to ensure that the characteristic 34 includes several peaks and troughs within the spectral range of a single peak of the Mach-Zehnder characteristic 33. Together, those conditions ensure that there is always at least one Fabry Pérot mode inside the channel bandwidth defined by the Mach-Zehnder multiplexer, that there will be a gain peak inside the Bragg reflector bandwidth regardless of the precise value of phase imbalance provided by the Mach-Zehnder, and, provided that the Bragg reflector bandwidth is coextensive with or lies within the absorption band of the fibre amplifier, that lasing can occur at any point in the spectrum across the full bandwidth of the Bragg reflector. A further desirable design criterion is that, in order to preclude the possibility of amplifier gain modulation

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being produced from inter-mode beating effects the frequency spacing of the Fabry Pérot modes, as determined by the external path distance between reflecting facet 10b and Bragg grating 14, is large compared with the reciprocal of the gain time constant of the amplifier 16.

If the antireflective coatings 10a are noticeably far from ideal, then there will be another frequency dependent element in the composite cavity, this resulting from the Fabry Pérot modes as determined by the optical path length between the ends of the semiconductor amplifier chip 10. In this instance two other desiderata come into play. First the Bragg reflector bandwidth should be larger than the mode spacing of the Fabry Pérot modes of the chip in order to ensure that there is at least one Fabry Pérot mode of the chip within the spectral band of the Bragg reflector 14. Second the bandwidth of a Fabry Pérot mode of the chip must be large compared with the bandwidth of a channel defined by the multiplexer so as to ensure that there is a lasing mode at all times.

With the foregoing criteria in mind, a typical example of an assembly as depicted in Figures 1 and 2 may have semiconductor chips 10 individually emitting over a gain-providing bandwidth in excess of 20nm pumping, an erbium fibre amplifier 16 with an optical path difference providing a channel spacing of about 10 GHz, semiconductor chips of a length providing Fabry Pérot modes with a bandwidth of about 0.75nm, and an optical path distance between reflecting facets 10b and the Bragg reflector 14 providing composite cavity Fabry Pérot modes at intervals of about 40 MHz.

Light of some arbitrary wavelength emitted by semiconductor chip 10·1 into Mach-Zehnder 12 will be divided by the Mach-Zehnder into two portions, one propagating in fibre 13 and the other propagating in the unused port of the Mach-Zehnder, port 25. As the wavelength of emission is progressivly changed, the proportion launched into the unused port 25 is swept repetitively between 0 and 100%. The spectral cavity that includes semiconductor chip 10·1 will lase at a wavelength for which the round trip losses of the cavity are at a minimum. This is a wavelength for which no light from chip 10·1 is launched into the unused

port 25 of the Mach-Zehnder. A similar situation holds in respect of semiconductor chip 10·2 but, since the zero power launch into unused port 25 is a straight-through condition of the Mach-Zehnder for one laser cavity and a cross-over condition for the other, it is clear that the two cavities can not lase at the same wavelength.

Attention is now turned to Figure 4 which schematically depicts an assembly constructed according to the same principles described above in relation to the construction of the assembly of Figure 2, the assembly of Figure 4 having an extra stage of Mach-Zehnder multiplexers. The components additional to those of the assembly of Figure 2 comprise two semiconductor optical amplifier chips 10·3, 10·4, and two further Mach-Zehnders 40, 41. The optical path difference of Mach-Zehnder 40 does not have to equal that of Mach-Zehnder 41 but, to ensure that there is a lasing frequency for each of the four chips 10·1 to 10·4 regardless of the phase difference provided by each of the three Mach-Zehnder, there should be a factor of at least two between the magnitude of the path difference of Mach-Zehnder 12 and that of each of the Mach-Zehnders 40, 41. The widest Mach-Zehnder mode spacing, as determined by the Mach-Zehnder with the smallest optical path difference, should still be smaller than the reflective bandwidth of the Bragg reflector. Similarly the narrowest Mach-Zehnder mode spacing, as determined by the Mach-Zehnder with the greatest optical path difference, should still be greater than the spacing of the Fabry Pérot modes defined between reflecting facets of the chips and the Bragg reflector so as to ensure that there is always an available lasing mode for each chip inside the wavelength range defined by that Bragg reflector.

Figure 5 schematically depicts an assembly similar to that of Figure 4 except for the place of the Mach-Zehnder multiplexer 12 of Figure 4 being taken by a polarisation beam-splitter 50 and associated two wavelength-dependent birefringent elements 51, 52. These birefringent elements 51, 52 may take the form of the fibre equivalents of Lyot depolarisers. Their function is to provide a wavelength to polarisation conversion mechanism.

To analyse the operation of the structure, the designations 'horizontal' and 'vertical' will be arbitrarily assigned to the states of polarisation of light that passes substantially without attenuation through the polarisation beam splitter respectively in a straight path and in a crossover path. For laser action, the emergence of light from the free port, port 55, of the polarisation beam splitter should be minimised. This in turn means that light from chips 10·1 and 10·2 should enter the polarisation beam splitter horizontally polarised while that from chips 10·3 and 10·4 should enter it vertically polarised. If the waveguide couplings between the chips and the polarisation beam splitter were constructed in polarisation maintaining waveguide there would be no need for the wavelength-sensitive birefringent elements 51 and 52 because, when such waveguides are employed, the orientation with which they are coupled to the polarisation beam splitter determines the state of polarisation of light entry, and hence the orientation can be chosen to provide the required states of polarisation. More usually it may be preferred to couple the chips to the polarisation beam splitter with waveguides that are not polarisation maintaining, in which case the state of polarisation of light is liable to evolve in an arbitrary and variable manner in its passage from the chips to the polarisation beam splitter due to the effects of stray birefringence in those waveguides. The function of each of the birefringent elements 51 and 52 is to provide a wavelength-sensitive further evolution of the state of polarisation, the wavelength sensitivity being such as to provide wavelengths within the emission bands of the chips for which the evolution has a magnitude that provides an input to the polarisation beam splitter that is substantially horizontal or vertical according to which particular one of the inputs to the polarisation beam splitter to which that particular birefringent element is connected.

It has been tacitly assumed that there is no significant evolution of state of polarisation between the polarisation beam splitter and the grating, and accordingly light reflected by the grating returns to the polarisation beam splitter with substantially the same state of polarisation as that with which it first emerged from the polarisation beam splitter. If there is

a serious risk that there could be an indeterminate amount of evolution of state of polarisation giving rise to the possibility of the light returning with the orthogonal state of polarisation, this can be prevented by the use of a further wavelength-dependent birefringent element (not shown), conveniently also a fibre equivalent of a Lyot depolariser interposed between the polarisation beam splitter and the grating.

In the case of the construction described with reference to Figure 4, the three Mach-Zehnders ensure that the four semiconductor chips 10·1 to 10·4 all lase at different wavelengths, thereby ensuring that there can be no optical interference between the four laser outputs. In the case of the construction described with reference to Figure 5, there is nothing to prevent the laser cavity that includes chip 10·1 or chip 10·2 from lasing at the same wavelength as either one of the laser cavities that respectively include chips 10·3 and 10·4, but in this instance optical interference is precluded because they are arranged to have orthogonal polarisation states.

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WE CLAIM:-

1. A laser assembly having a set of N reflectors (10b) optically coupled via a set of N optical amplifiers (10) and an Nx1 wavelength multiplexer (12) with a partially reflecting common reflector (14) so as to define N laser cavities providing an N-way wavelength-multiplexed output from the common reflector.

2. An assembly as claimed in claim 1, wherein the N optical amplifiers are semiconductor optical amplifiers.

3. An assembly as claimed in claim 1 or 2, wherein the Nx1 wavelength multiplexer includes at least one Mach-Zehnder waveguide structure.

4. A laser assemblage having two laser assemblies as claimed in claim 1, 2 or 3 sharing the same common reflector via a polarisation beam splitter (50).

5. An optical amplifier optically pumped by a laser assembly as claimed in claim 1, 2 or 3, or a laser assemblage as claimed in claim 4.

6. In an optically pumped optical amplifier having a set of N optical pump amplifier sources provided with optical feedback to make the sources lase, a method of controlling the wavelength relationship between the emission wavelengths of the N lasing optical pump sources by providing the feedback in part by a partial reflector that is common to each lasing source via an Nx1 wavelength multiplexing element to provide a combined wavelength multiplexed optical pump output from the partial reflector.

7. A method as claimed in claim 6, wherein the N optical amplifiers are semiconductor optical amplifiers.

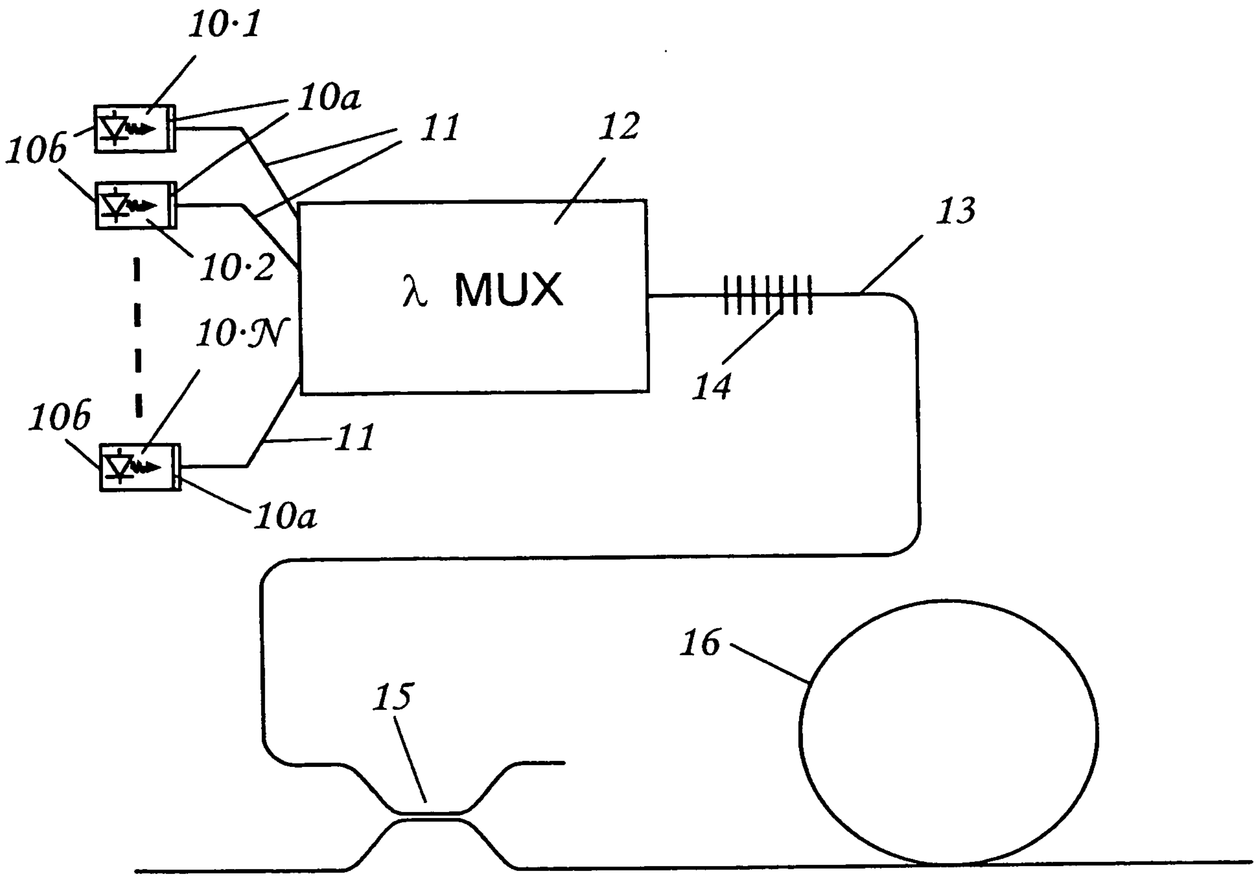
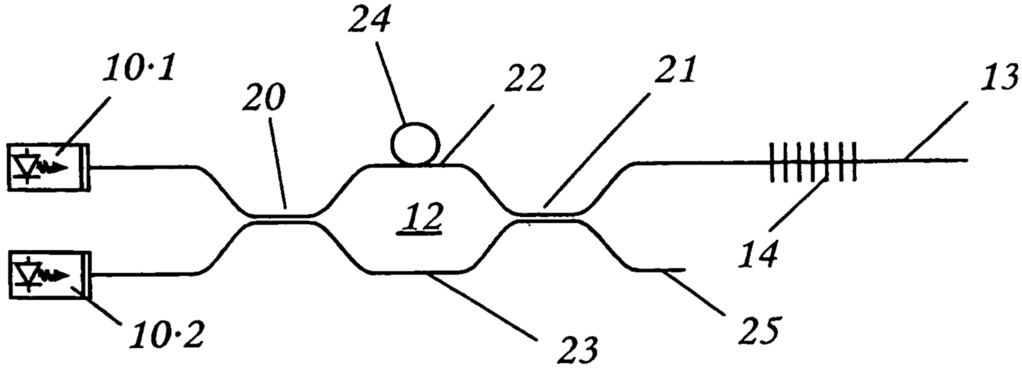

10·1
10a
10b
11
12
λ MUX
13
10·2
10·N
14
10b
11
10a
16
15

Fig. 1.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10·1
20
22
21
13
12
14
10·2
23
25

Fig. 2.

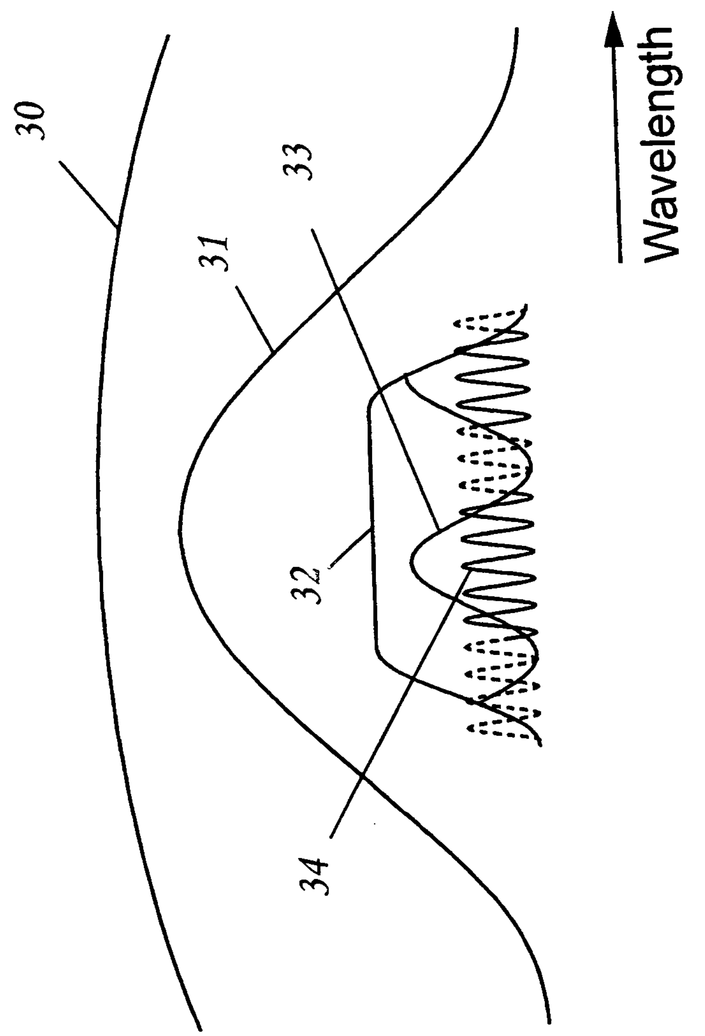

Fig. 3.

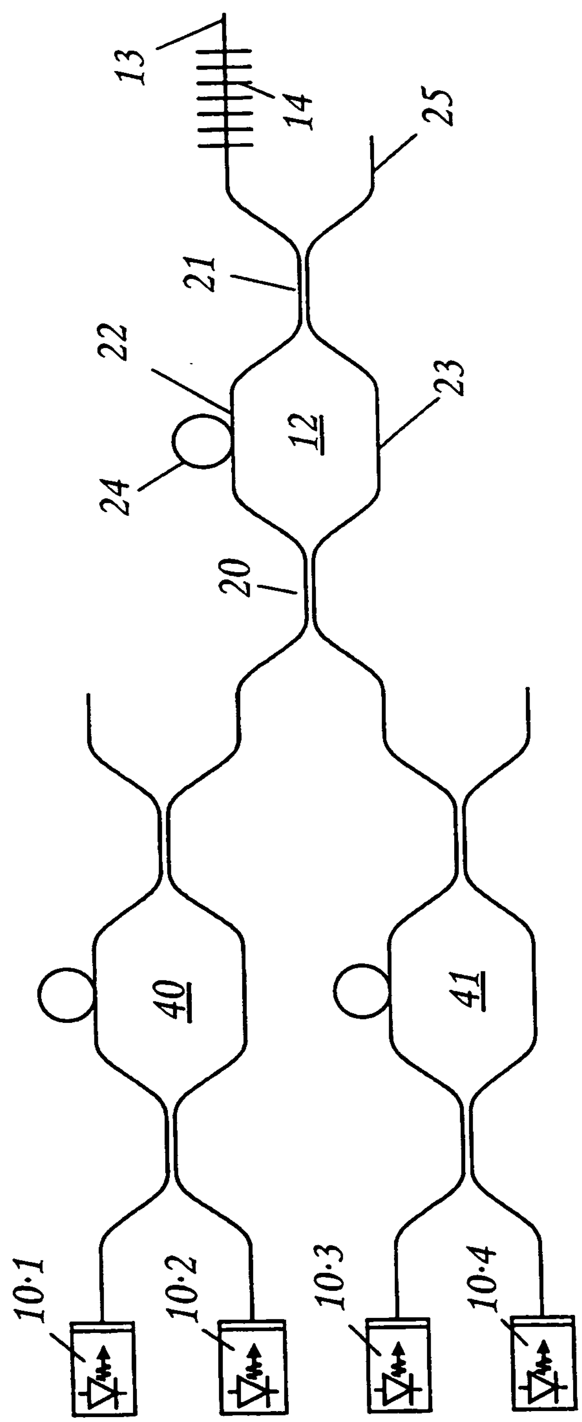

Fig. 4.

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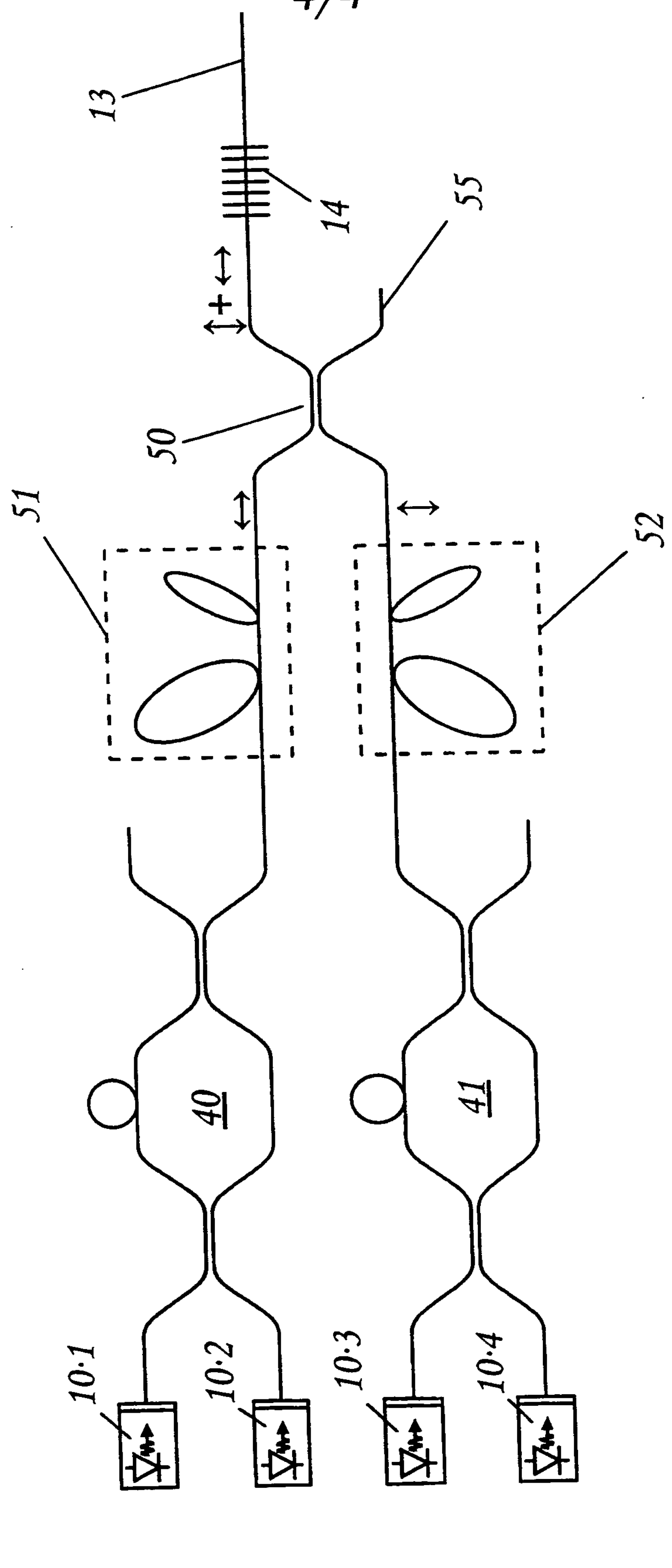

Fig. 5.

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INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/25 H01S3/0941 H01S3/23

According to International Patent Classification (IPC) or to both national classification and IPC

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IPC 6 H01S H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	see figure 1	6,7

X	GILES C R ET AL: "SIMULTANEOUS WAVELENGTH-STABILIZATION OF 980-NM PUMP LASERS" IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 6, no. 8, 1 August 1994, pages 907-909, XP000465479 see figure 1	1,2,6,7

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[X] Further documents are listed in the continuation of box C.

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 012, no. 095 (P-681), 29 March 1988 & JP 62 229105 A (NIPPON TELEGR & TELEPH CORP), 7 October 1987	1,2
A	see abstract ---	4-6
A	EP 0 704 949 A (NORTHERN TELECOM LTD) 3 April 1996 cited in the application	1-3
Y	see the whole document ---	6,7
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INTERNATIONAL SEARCH REPORT

Information on patent family members

Int   ional Application No
PCT/GB 98/00171

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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